

Optical analogies to quantum states and coherent detection of pseudorandom phase sequence

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Abstract

The key to optical analogy to a multi-particle quantum system is the scalable property. Optical fields modulated with pseudorandom phase sequences is an interesting solution. By utilizing the properties of pseudorandom sequences, mixing multiple optical fields are distinguished by using coherent detection and correlation analysis that are mature methods in optical communication. In this paper, we utilize the methods to investigate optical analogies to multi-particle quantum states. In order to demonstrate the feasibility, numerical simulations are carried out in the paper, which is helpful to the experimental verification in the future.

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I. INTRODUCTION

Quantum computation is a revolutionary approach to speed up many classical algorithms exponentially, due to quantum superposition and entanglement [1, 2]. However, it is difficult to construct a powerful enough quantum computer to implement sufficiently complex quantum algorithms, which inspires some researches on the simulations of quantum states and quantum computation using classical optical fields [3–7]. In these researches, the simulations can be realized using classical optical fields to introduce extra freedoms, such as orbital angular momentum, frequency, and time bins [8], which, however, might be hard to simulate a quantum state with arbitrary number of quantum particles.

Recently, a method is proposed to simulate quantum states and quantum computation using the classical optical fields modulated by pseudorandom phase sequences [9–12]. In the method, two orthogonal modes of the optical fields, such as polarization and spatial mode [13], are encoded as qubit $|0\rangle$ and $|1\rangle$, which demonstrate the similar properties to quantum states, such as superposition even entanglement. However, the physical meaning of the superpositions is different from quantum states. A measurement of certain quantum states will generally produce a random result, and the ensemble averaging after many measurements can yield a physical measurement result. In Ref. [11], a new conception of pseudorandom phase ensemble is introduced. In the theoretical framework, the nonlocal properties of quantum entanglement can be simulated by using classical fields modulated with pseudorandom phase sequences [9], which contain all properties of the coherent superposition of orthogonal modes and the orthogonality, closure and balance of pseudorandom phase sequences [14–16]. It is interesting to make analogies between a single quantum particle with a phase code in a pseudorandom phase sequence, and quantum ensemble with pseudorandom phase sequences. From these analogies, we could conclude that pseudorandom phase sequences not only can qualify independence and distinguishability for each classical field, also can provide similar randomness to quantum measurements. Moreover, the randomness is ergodic within one sequence cycle, which means a higher efficiency than the ergodicity of real quantum measurement system. Furthermore, the states with arbitrary number of quantum particles can be simulated by classical fields with same number of pseudorandom sequences whose number increase linearly with their length. It means the simulation is effective and without limitation.

In this paper, we discuss the coherent detection and correlation analysis method to distinguish the optical fields modulated with pseudorandom phase sequences, and then to simulate the multi-particle quantum states, such as GHZ state and W state. Furthermore, we construct an optical analogy to the entangled state as the result of the modular exponential function in Shor's algorithm [17] to factorize $15 = 3 \times 5$. We demonstrate the result state how to be represented by classical fields and measured by the coherent detection and correlation analysis. The computer simulation software adopted in this paper is the well-known optical communication simulation software OPTISYSTEM.

II. ORTHOGONALITY OF PSEUDORANDOM PHASE SEQUENCE AND COHERENT DETECTION OF OPTICAL FIELDS

In modern communication, the pseudorandom code is widely used in CDMA (Code Division Multiple Access) to distinguish different users [14–16]. The orthogonality of the code can enable the coherent detection in communication, which can transfer target information to the users with a corresponding code in a same channel used by many users. Ref. [10] proposed that quantum entanglement and quantum state can be simulated by classical optical fields modulated by this pseudorandom phase sequences, which make use of the coherent superposition of classical optical fields and the orthogonality, closure and balance property of pseudorandom phase sequences. Especially, the simulation of the non-locality in quantum mechanism is essentially utilize the non-locality of the phase of classical fields [9, 11]. These properties can be demonstrated by the coherent detection of classical optical fields. Here, we will utilize the mature optical coherent communication technology and the simulation software, OPTISYSTEM, to investigate the orthogonality and indistinguishability of multi-optical-field realized by orthogonal pseudorandom phase sequences.

According to Ref. [10], we encode two orthogonal polarization modes of classical fields as quantum bits (qubits) $|0\rangle$ and $|1\rangle$. In order to distinguish different classical fields, we modulated the fields with pseudorandom phase sequences. These pseudorandom phase sequences, except the all-zero $\lambda^{(0)}$ sequence, are the expressions as following,

$$\begin{aligned}\lambda^{(1)} &= \left\{ \frac{\pi}{2} \ 0 \ 0 \ \frac{\pi}{2} \ 0 \ \frac{\pi}{2} \ \frac{\pi}{2} \ 0 \right\}, \\ \lambda^{(2)} &= \left\{ \frac{\pi}{2} \ \frac{\pi}{2} \ 0 \ 0 \ \frac{\pi}{2} \ 0 \ \frac{\pi}{2} \ 0 \right\},\end{aligned}\tag{1}$$

$$\begin{aligned}
\lambda^{(3)} &= \left\{ \frac{\pi}{2} \frac{\pi}{2} \frac{\pi}{2} 0 0 \frac{\pi}{2} 0 0 \right\}, \\
\lambda^{(4)} &= \left\{ 0 \frac{\pi}{2} \frac{\pi}{2} \frac{\pi}{2} 0 0 \frac{\pi}{2} 0 \right\}, \\
\lambda^{(5)} &= \left\{ \frac{\pi}{2} 0 \frac{\pi}{2} \frac{\pi}{2} \frac{\pi}{2} 0 0 0 \right\}, \\
\lambda^{(6)} &= \left\{ 0 \frac{\pi}{2} 0 \frac{\pi}{2} \frac{\pi}{2} \frac{\pi}{2} 0 0 \right\}, \\
\lambda^{(7)} &= \left\{ 0 0 \frac{\pi}{2} 0 \frac{\pi}{2} \frac{\pi}{2} \frac{\pi}{2} 0 \right\},
\end{aligned}$$

where the sequences are GF(2) with $[0, \frac{\pi}{2}]$ instead of GF(4) with $[0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}]$ in Ref. [9]. Due to the orthogonality of polarization modes, the pseudorandom phase sequences only need to distinguish the classical fields with same polarization mode. In this section, we mainly focus on the characteristic of the classical fields with same polarization mode after the modulation of pseudorandom phase sequences. We choose $\lambda^{(1)}$ to modulate the classical fields labeled as signal light (SO), the electric field component of the field is:

$$E_S(t) = A_S e^{-i(\omega t + \lambda_k^{(1)})}, \quad (2)$$

where A_S, ω are the amplitude and frequency of the classical optical field respectively, and $\lambda_k^{(1)}$ is the phase code of $\lambda^{(1)}$ at time t . In order to do the coherent detection of pseudorandom phase sequence, we design a detection scheme shown in Fig. 1, according to the method used in coherent optical communication [14–16]. The detection scheme makes the local light (LO) and signal light (SO) interfere with each other. In order to ensure the coherence of them, these two beams are obtained by splitting the same source by a beam splitter. The field of local light can be expressed as:

$$E_L(t) = A_L e^{-i(\omega t + \lambda_k^{(n)})}, \quad (3)$$

where $\lambda^{(n)}$ can be arbitrary sequences in Eq. (1) and the amplitude $A_L = A_S$. After the coherent superposition through the coupler, the output lights can be expressed respectively,

$$\begin{pmatrix} E_1(t) \\ E_2(t) \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & i \\ -i & 1 \end{pmatrix} \begin{pmatrix} E_S(t) \\ E_L(t) \end{pmatrix} = \frac{A_S}{\sqrt{2}} \begin{pmatrix} e^{-i(\omega t + \lambda_k^{(1)})} + i e^{-i(\omega t + \lambda_k^{(n)})} \\ -i e^{-i(\omega t + \lambda_k^{(1)})} + e^{-i(\omega t + \lambda_k^{(n)})} \end{pmatrix}. \quad (4)$$

Then, the output electric signals of photodetectors (PDs) D_1 and D_2 is proportional to

$$\begin{aligned}
I_1 &= \mu |E_1(t)|^2 = \mu A_s^2 \left[1 + \sin(\lambda_k^{(1)} - \lambda_k^{(n)}) \right], \\
I_2 &= \mu |E_2(t)|^2 = \mu A_s^2 \left[1 - \sin(\lambda_k^{(1)} - \lambda_k^{(n)}) \right],
\end{aligned} \quad (5)$$

where μ is the parameter related to the sensitivity of PDs. Finally, after the correlation analysis of two electric signal, we can obtain the following according to the orthogonality of pseudorandom sequence,

$$C = \langle I_1 I_2 \rangle = \frac{\mu^2 A_s^4 \Delta T}{2} \sum_{k=1}^8 \left[1 + \cos 2 \left(\lambda_k^{(1)} - \lambda_k^{(n)} \right) \right] = \begin{cases} 8\mu^2 A_s^4 \Delta T, n = 1 \\ 4\mu^2 A_s^4 \Delta T, n \neq 1 \end{cases}, \quad (6)$$

where ΔT is the sequence period.

To verify the above scheme, we utilize OPTISYSTEM to simulate it on the computer. Fig. 2 shows the electric signals of two PDs within a sequence period. Fig. 3 shows the result after the correlation of the optical fields modulate with different sequences, from which we can find out when the modulation sequences of local light and signal light is same, the value of correlation function is one time larger than that in other cases. Hence, the orthogonality of pseudorandom sequences can be used to distinguish the optical fields modulated by different phase sequences. By using the polarization beam splitter, we can easily realize the detection of the classical fields with two polarization modes.

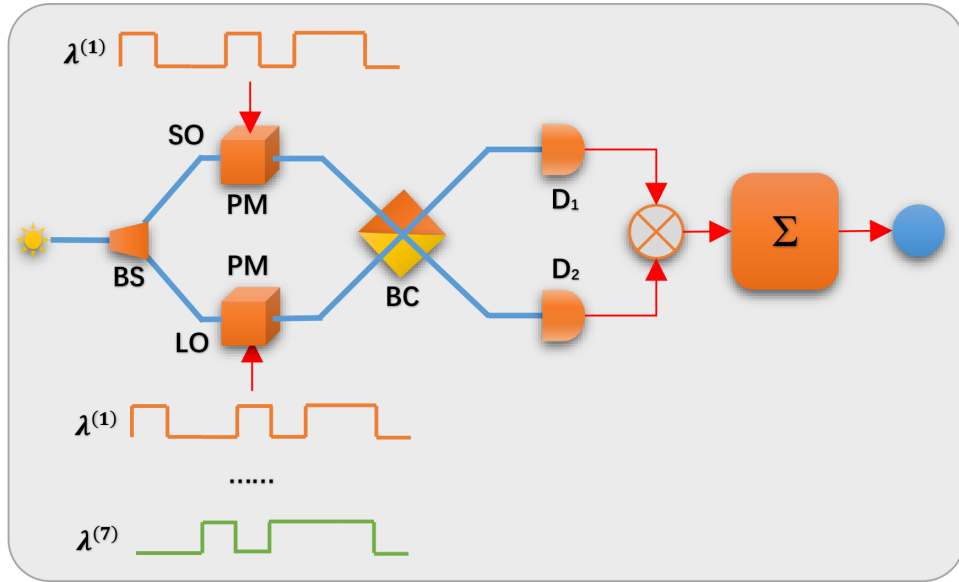


FIG. 1: The scheme of the coherent detection of pseudorandom phase sequence, where SO: the signal light, LO: the local light, BS: beam splitter, PM: phase modulator, BC: beam coupler, D_1 and D_2 : photodetectors, \otimes : multiplier and Σ : integrator (integrate over entire sequence period).

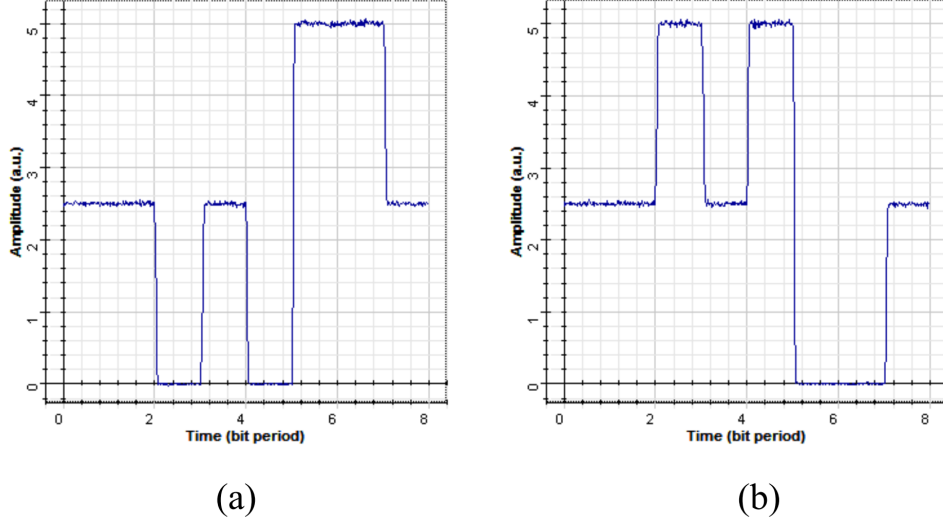


FIG. 2: The electric signals of D_1 (a) and D_2 (b) when the sequence of LO is $\lambda^{(5)}$.

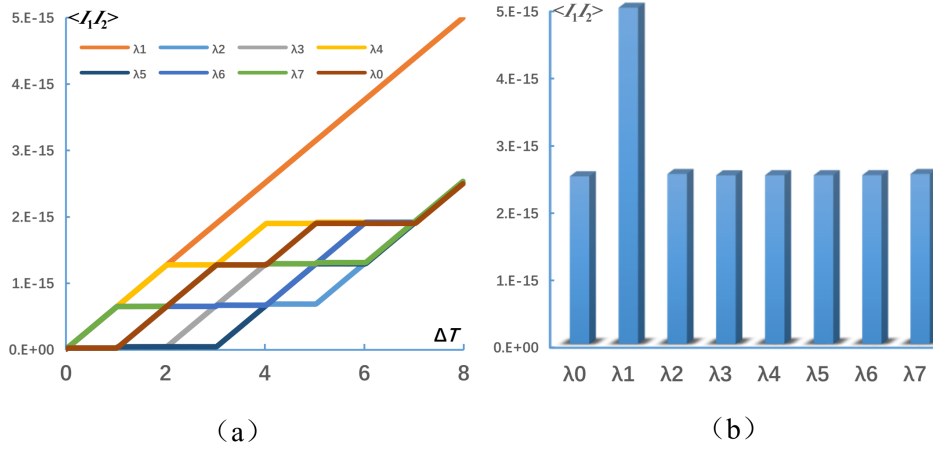


FIG. 3: The correlation analysis result between signal light and local light modulated with different pseudorandom sequence, where (a) is the integral of correlation function with different sequence period ΔT , and (b) is the final result of integral of different LO with $\lambda_0 \sim \lambda_7$ represent sequences $\lambda^{(0)} \sim \lambda^{(7)}$.

III. ANALOGY TO THE THREE-PARTICLE QUANTUM STATES

Ref. [10] demonstrates the classical field simulation of three-particle quantum states, which are a product state, GHZ state and W state. To construct product state, we arbitrarily choose three sequences from the pseudorandom sequences set to modulate the classical fields,

and obtain:

$$\begin{aligned} E_1(t) &= (A_{\uparrow} + A_{\rightarrow}) e^{-i(\omega t + \lambda_k^{(1)})}, \\ E_2(t) &= (A_{\uparrow} + A_{\rightarrow}) e^{-i(\omega t + \lambda_k^{(2)})}, \\ E_3(t) &= (A_{\uparrow} + A_{\rightarrow}) e^{-i(\omega t + \lambda_k^{(3)})}, \end{aligned} \quad (7)$$

where A_{\uparrow} and A_{\rightarrow} denote the amplitudes of two orthogonal polarization modes $|0\rangle$ and $|1\rangle$, respectively. We adopt the scheme in Fig. 4 to realize this state.

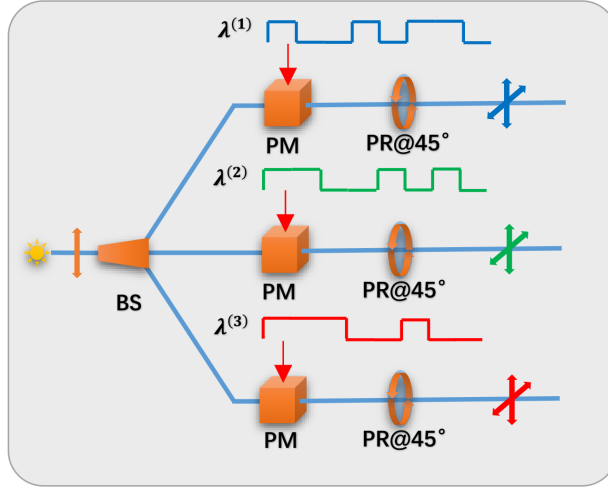


FIG. 4: The scheme to realize the simulation of quantum product state, where PR@45°: 45° polarization rotators.

According to Ref. [10], the classical field simulations of GHZ state can be written as following:

$$\begin{aligned} E_1(t) &= A_{\uparrow} e^{-i(\omega t + \lambda_k^{(1)})} + A_{\rightarrow} e^{-i(\omega t + \lambda_k^{(2)})}, \\ E_2(t) &= A_{\uparrow} e^{-i(\omega t + \lambda_k^{(2)})} + A_{\rightarrow} e^{-i(\omega t + \lambda_k^{(3)})}, \\ E_3(t) &= A_{\uparrow} e^{-i(\omega t + \lambda_k^{(3)})} + A_{\rightarrow} e^{-i(\omega t + \lambda_k^{(1)})}, \end{aligned} \quad (8)$$

which can be realized by mode exchange of the produce state in equation (7) using polarization beam splitters (PBSs), as shown in Fig. 6. Then we can express the classical field simulations of W state as following:

$$\begin{aligned} E_1(t) &= A_{\uparrow} e^{-i(\omega t + \lambda_k^{(1)})} + A_{\rightarrow} e^{-i(\omega t + \lambda_k^{(2)})} + A_{\rightarrow} e^{-i(\omega t + \lambda_k^{(3)})}, \\ E_2(t) &= A_{\uparrow} e^{-i(\omega t + \lambda_k^{(1)})} + A_{\rightarrow} e^{-i(\omega t + \lambda_k^{(2)})} + A_{\rightarrow} e^{-i(\omega t + \lambda_k^{(3)})}, \\ E_3(t) &= A_{\uparrow} e^{-i(\omega t + \lambda_k^{(1)})} + A_{\rightarrow} e^{-i(\omega t + \lambda_k^{(2)})} + A_{\rightarrow} e^{-i(\omega t + \lambda_k^{(3)})}, \end{aligned} \quad (9)$$

which can be realized by mode combination and split of the initial state using the beam coupler and splitter, as shown in Fig. 7.

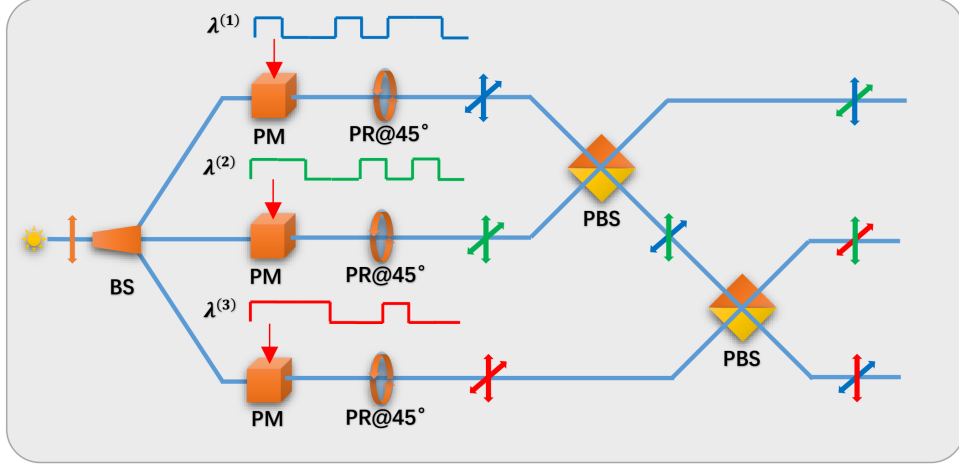


FIG. 5: The scheme to realize the simulation of quantum GHZ state, where PBS: polarization beam splitter, PR@45°: 45° polarization rotators.

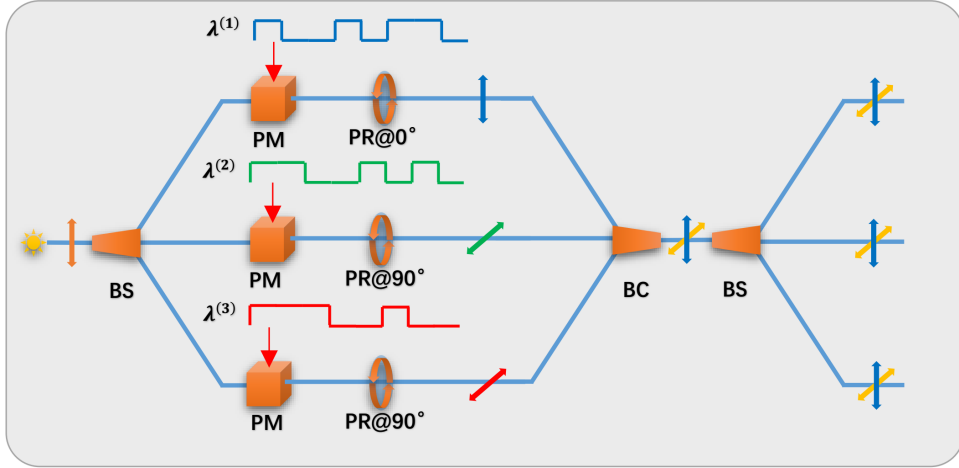


FIG. 6: The scheme to realize the simulation of quantum W state, where BC: beam coupler, BS: beam splitter, PR@0°: 0° polarization rotators, PR@90°: 90° polarization rotators.

Here, we make use of the method mentioned in Section II to investigate the relation between the coherent detection of pseudorandom sequence and the simulation of quantum states. Because of each field of GHZ state and W state has two orthogonal polarization modes, the detection scheme need to split two modes using a PBS, as shown in Fig. 7. By using OPTISYSTEM, we can easily construct a simulation model to realize the schemes

as shown in Fig. 5 and Fig. 7 for GHZ state. Fig. 8 shows the electric signals of PDs after the interference between the first field and LO, where the LOs are modulated by three pseudorandom sequences $\lambda^{(1)}$, $\lambda^{(2)}$, $\lambda^{(3)}$ respectively, and (a) and (b) represent two orthogonal polarization modes respectively. Then, we can obtain the correlation function of three fields, as shown in Fig. 9. After subtracting the correlation function with constant and normalization, we can express the measurement result as the M matrix mentioned in Ref. [10] as following:

$$M = \begin{pmatrix} (1,0) & (0,1) & 0 \\ 0 & (1,0) & (0,1) \\ (0,1) & 0 & (1,0) \end{pmatrix}, \quad (10)$$

where the rows denote classical fields $E_1(t)$, $E_2(t)$ and $E_3(t)$, the columns denote the pseudorandom sequences $\lambda^{(1)}$, $\lambda^{(2)}$, $\lambda^{(3)}$, and the matrix elements denote the states of mode ((1,0) denotes A_{\uparrow} exists, (0,1) denotes A_{\rightarrow} exists, (1,1) denotes all modes exist, 0 denote none mode exists).

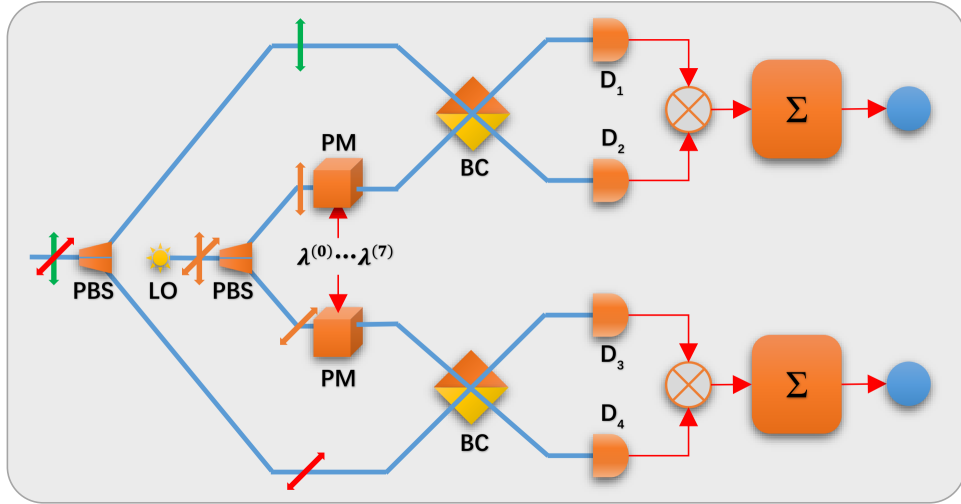


FIG. 7: The coherent detection scheme of GHZ state and W state, where PBS: polarization beam splitter and BC: beam coupler.

Meanwhile, we can simulate W state. Fig. 10 show the electric signals of PDs after the interference between the first field of W state and LO. Furthermore, we can obtain the correlation function of three fields, as shown in Fig. 11. After subtracting the correlation function with constant and normalization, we can express the M matrix of W state as

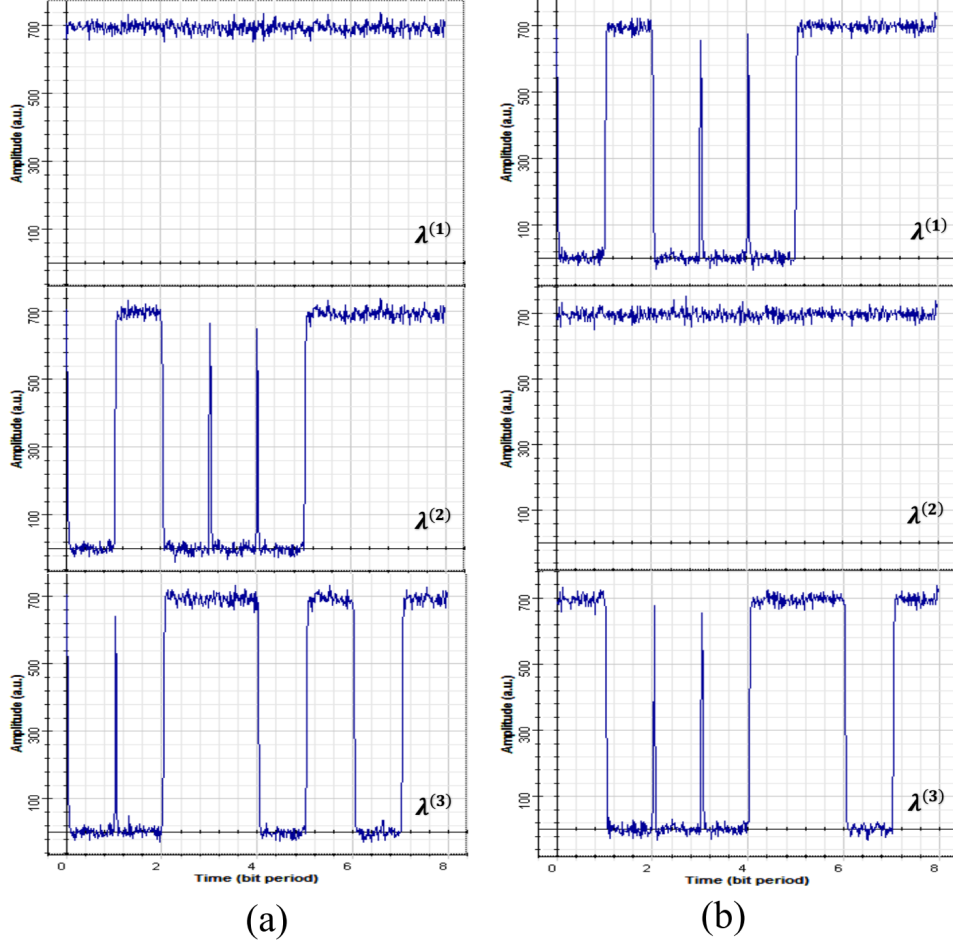


FIG. 8: The electric signal of the coherent detection of the first field of GHZ state, where (a) and (b) represent two orthogonal modes A_{\uparrow} and A_{\rightarrow} respectively.

following:

$$M = \begin{pmatrix} (1,0) & (0,1) & (0,1) \\ (1,0) & (0,1) & (0,1) \\ (1,0) & (0,1) & (0,1) \end{pmatrix}. \quad (11)$$

IV. ANALOGY TO THE RESULT STATE FOR FACTORIZING $15 = 3 \times 5$

Shor's algorithm is a crucial algorithm displaying the exponential speed-up of quantum computation. Shor's algorithm to factorize $15 = 3 \times 5$ has been verified by NMR experiment [18]. The key to Shor's algorithm to factorize positive integer N is to calculate the modular exponential function $f(x) = a^x \bmod N$, where a is positive coprime integer, and obtain the

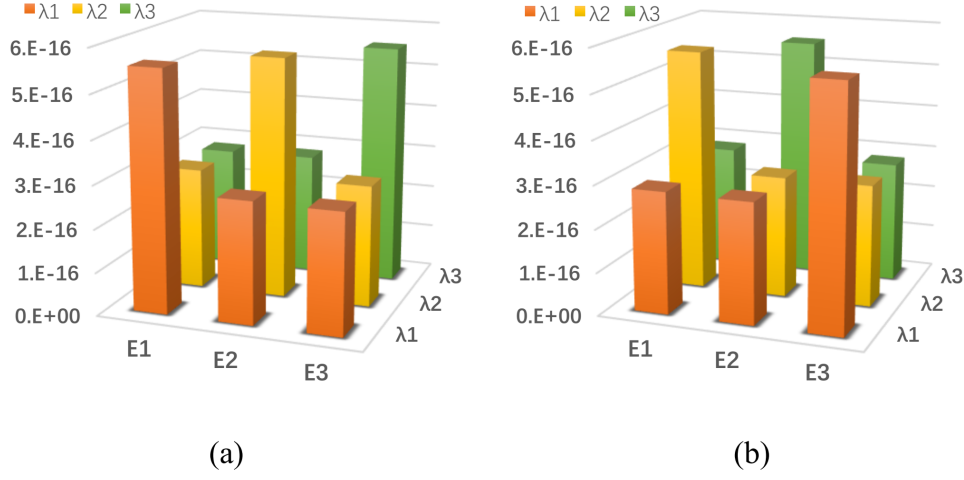


FIG. 9: The correlation measurement result of GHZ state, where (a) and (b) represent two orthogonal modes A_{\uparrow} and A_{\rightarrow} respectively, $E1$, $E2$, $E3$ three fields and $\lambda1$, $\lambda2$, $\lambda3$ the consequences $\lambda^{(1)}$, $\lambda^{(2)}$, $\lambda^{(3)}$ modulating on LO.

result state that is an eight-particle entangled state, then to apply the fourier transformation on the state to obtain the period of it. According to Ref. [10], we can obtain optical analogy to the entangled state as the result of the modular exponential function. The classical fields are modulated by 8 pseudorandom sequences. After a series of the polarization operations as shown in Fig. 12, the required state can be obtained,

$$\begin{aligned}
 |\psi'_1\rangle &= \left(e^{i\lambda^{(1)}} + e^{i\lambda^{(2)}} + e^{i\lambda^{(3)}} + e^{i\lambda^{(4)}} \right) (|0\rangle + |1\rangle), \\
 |\psi'_2\rangle &= \left(e^{i\lambda^{(2)}} + e^{i\lambda^{(3)}} + e^{i\lambda^{(4)}} + e^{i\lambda^{(5)}} \right) (|0\rangle + |1\rangle), \\
 |\psi'_3\rangle &= \left(e^{i\lambda^{(3)}} + e^{i\lambda^{(4)}} \right) |0\rangle + \left(e^{i\lambda^{(5)}} + e^{i\lambda^{(6)}} \right) |1\rangle, \\
 |\psi'_4\rangle &= \left(e^{i\lambda^{(4)}} + e^{i\lambda^{(6)}} \right) |0\rangle + \left(e^{i\lambda^{(5)}} + e^{i\lambda^{(7)}} \right) |1\rangle, \\
 |\psi'_5\rangle &= \left(e^{i\lambda^{(5)}} + e^{i\lambda^{(6)}} + e^{i\lambda^{(7)}} \right) |0\rangle + e^{i\lambda^{(8)}} |1\rangle, \\
 |\psi'_6\rangle &= e^{i\lambda^{(6)}} |0\rangle + \left(e^{i\lambda^{(7)}} + e^{i\lambda^{(8)}} + e^{i\lambda^{(1)}} \right) |1\rangle, \\
 |\psi'_7\rangle &= \left(e^{i\lambda^{(7)}} + e^{i\lambda^{(1)}} + e^{i\lambda^{(2)}} \right) |0\rangle + e^{i\lambda^{(8)}} |1\rangle, \\
 |\psi'_8\rangle &= \left(e^{i\lambda^{(8)}} + e^{i\lambda^{(2)}} \right) |0\rangle + \left(e^{i\lambda^{(1)}} + e^{i\lambda^{(3)}} \right) |1\rangle.
 \end{aligned} \tag{12}$$

By using OPTISYSTEM, we constructe a simulation model to realize the schemes as shown Fig. 12 to obtain the result of the modular exponential function. Then the final result

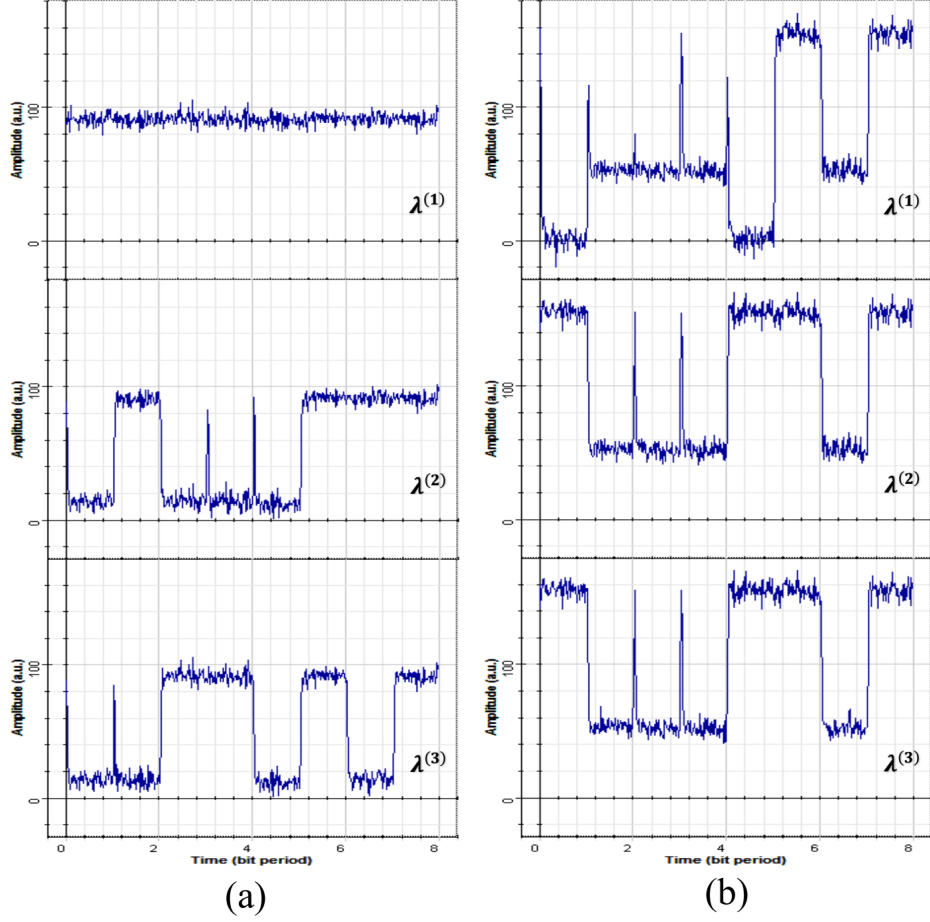


FIG. 10: The electric signal of the coherent detection of the first field of W state, where (a) and (b) represent two orthogonal modes A_{\uparrow} and A_{\rightarrow} respectively.

fields are coherently detected and the M matrix can be obtained. The schematic diagram of computer simulation is shown in Fig. 13. Firstly, the initial state can be prepared by the method as shown in Fig. 4, that is, modulate 8 classical fields $E_1 \sim E_8$ with 8 pseudorandom sequences in Eq. (1) respectively, and then rotate the polarization of each field by 45° and evolve into mode superposition states. After numerically simulating a complex gate array, we obtain the output fields and electric signals of PDs after the interference between each fields and LO. Finally, the correlation results are obtained, subtracted by the constant part and normalized, as shown in Fig. 14. After the threshold discrimination and binarization

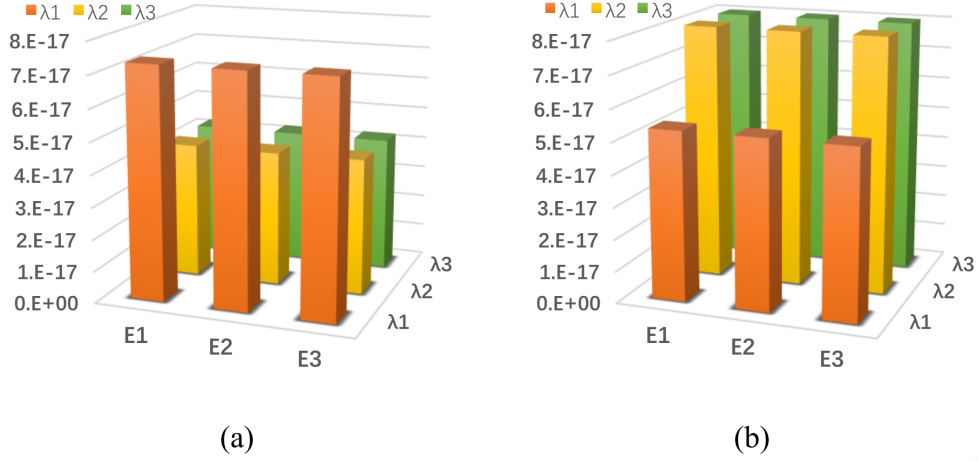


FIG. 11: The correlation measurement result of W state, where (a) and (b) represent two orthogonal modes A_{\uparrow} and A_{\rightarrow} respectively, $E1$, $E2$, $E3$ three fields and $\lambda1$, $\lambda2$, $\lambda3$ the consequences $\lambda^{(1)}$, $\lambda^{(2)}$, $\lambda^{(3)}$ modulating on LO.

of results, we can express the measurement results as the M matrix, which is:

$$M = \begin{pmatrix} (1,1) & (1,1) & (1,1) & (1,1) & 0 & 0 & 0 & 0 \\ 0 & (1,1) & (1,1) & (1,1) & (1,1) & 0 & 0 & 0 \\ 0 & 0 & (1,0) & (1,0) & (0,1) & (0,1) & 0 & 0 \\ 0 & 0 & 0 & (1,0) & (0,1) & (1,0) & (0,1) & 0 \\ 0 & 0 & 0 & 0 & (1,0) & (1,0) & (1,0) & (0,1) \\ (0,1) & 0 & 0 & 0 & 0 & (1,0) & (0,1) & (0,1) \\ (1,0) & (1,0) & 0 & 0 & 0 & 0 & (1,0) & (0,1) \\ (0,1) & (1,0) & (0,1) & 0 & 0 & 0 & 0 & (1,0) \end{pmatrix} \quad (13)$$

Using the sequence permutation scheme mentioned in Ref. [10], we can obtain the simulated states:

$$\begin{aligned} |\Psi'\rangle = & (|0\rangle + |4\rangle + |8\rangle + |12\rangle) |1\rangle \\ & + (|1\rangle + |5\rangle + |9\rangle + |13\rangle) |7\rangle \\ & + (|2\rangle + |6\rangle + |10\rangle + |14\rangle) |4\rangle \\ & + (|3\rangle + |7\rangle + |11\rangle + |15\rangle) |13\rangle. \end{aligned} \quad (14)$$

There are four kinds of superposition classified from last four qubits containing the values of $f(x)$ ($|1\rangle$, $|7\rangle$, $|4\rangle$ and $|13\rangle$) in output states, which means the period of $f(x) = 7^x \bmod 15$

is $r = 4$. It is worth noting that, different from quantum computing, we obtain the expected period of without operating quantum Fourier transformation [12].

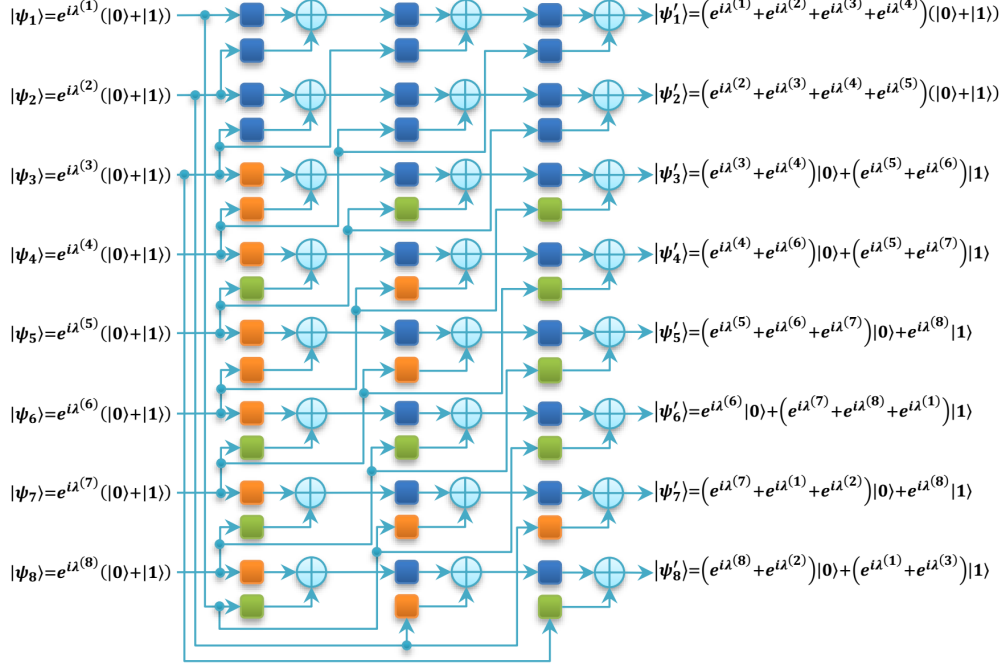


FIG. 12: Mode transformation gate matrix, where the blue block denotes all modes pass, the orange block A_{\uparrow} mode ($|0\rangle$) passes, and the green block A_{\downarrow} mode passes ($|1\rangle$).

V. CONCLUSIONS

In this paper, we utilize numerical simulations to prove the feasibility of coherent detection and correlation analysis to distinguish mixing classical fields with pseudorandom phase sequences. Due to much bigger Hilbert space spanned by the classical fields than quantum states [9], we might realize optical analogies to any quantum states. A rigorous proof will be discussed in the future paper.

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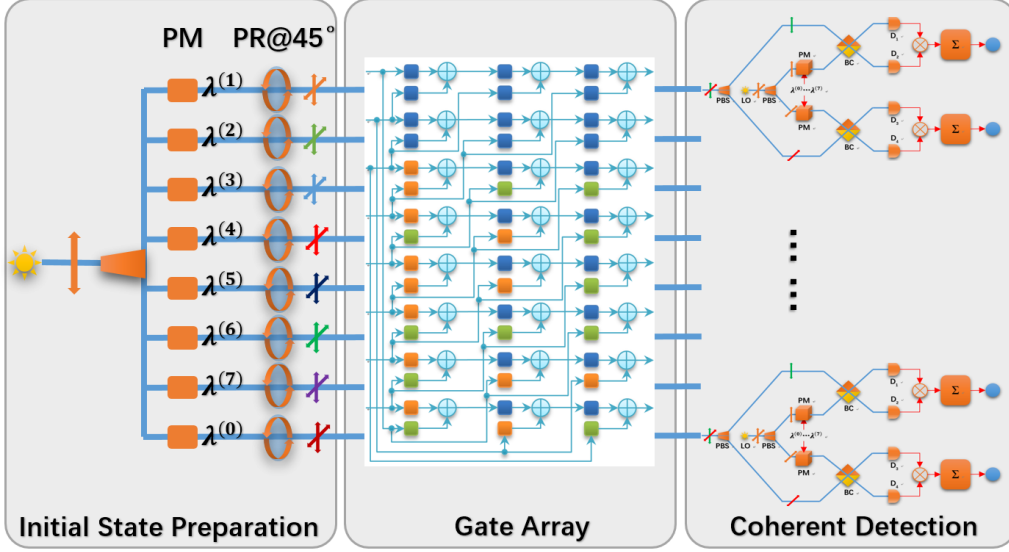


FIG. 13: The computer simulation scheme of algorithm factorizing $15 = 3 \times 5$.

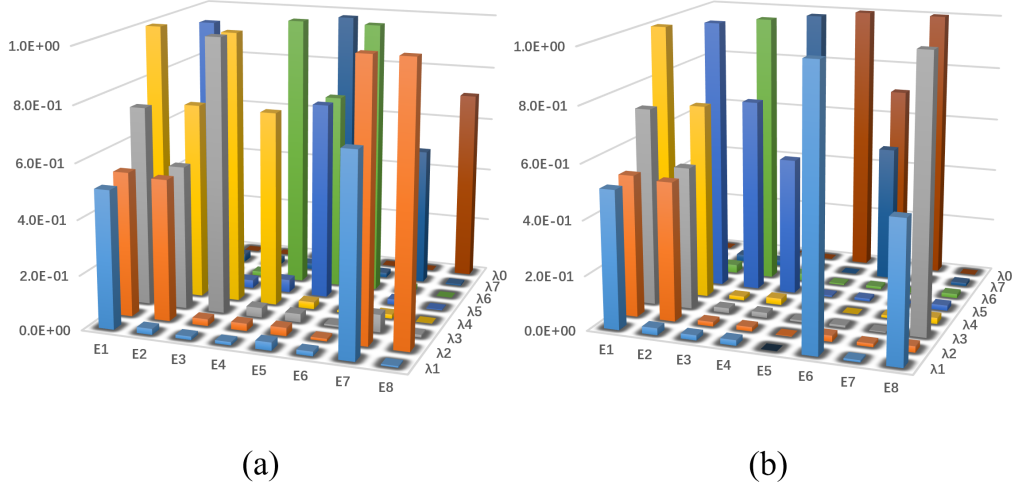


FIG. 14: The correlation measurement result of the superposition state of the factorizing algorithm: (a) for mode A_{\uparrow} , and (b) for mode A_{\rightarrow} , where $E1 \sim E8$ represents $E_1 \sim E_8$ classical fields, and $\lambda0 \sim \lambda7$ the pseudorandom sequences modulated on LO $\lambda^{(0)} \sim \lambda^{(7)}$.

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Fig. 1 The scheme of the coherent detection of pseudorandom phase sequence, where SO: the signal light, LO: the local light, BS: beam splitter, PM: phase modulator, BC: beam coupler, D_1 and D_2 : photodetectors, \otimes : multiplier and Σ : integrator (integrate over entire sequence period).

Fig. 2 The electric signals of D_1 (a) and D_2 (b) when the sequence of LO is $\lambda^{(5)}$.

Fig. 3 The correlation analysis result between signal light and local light modulated with different pseudorandom sequence, where (a) is the intergral of correlation function with different sequence period ΔT , and (b) is the final result of intergral of different LO with $\lambda_0 \sim \lambda_7$ represent sequences $\lambda^{(0)} \sim \lambda^{(7)}$.

Fig. 4 The sheme to realize the simulation of quantum product state, where PR@45°: 45° polarization rotators.

Fig. 5 The scheme to realize the simulation of quantum GHZ state, where PBS: polarization beam splitter, PR@45°: 45° polarization rotators.

Fig. 6 The sheme to realize the simulation of quantum W state, where BC: beam coupler, BS: beam splitter, PR@0°: 0° polarization rotators, PR@90°: 90° polarization rotators.

Fig. 7 The coherent detection scheme of GHZ state and W state, where PBS: polarization beam splitter and BC: beam coupler.

Fig. 8 The electric signal of the coherent detection of the first field of GHZ state, where (a) and (b) represent two orthogonal modes A_{\uparrow} and A_{\rightarrow} respectively.

Fig. 9 The correlation measurement result of GHZ state, where (a) and (b) represent two orthogonal modes A_{\uparrow} and A_{\rightarrow} respectively, $E1$, $E2$, $E3$ three fields and λ_1 , λ_2 , λ_3 the consequences $\lambda^{(1)}$, $\lambda^{(2)}$, $\lambda^{(3)}$ modulating on LO.

Fig. 10 The electric signal of the coherent detection of the first field of W state, where (a) and (b) represent two orthogonal modes A_{\uparrow} and A_{\rightarrow} respectively.

Fig. 11 The correlation measurement result of W state, where (a) and (b) represent two orthogonal modes A_{\uparrow} and A_{\rightarrow} respectively, $E1$, $E2$, $E3$ three fields and λ_1 , λ_2 , λ_3 the consequences $\lambda^{(1)}$, $\lambda^{(2)}$, $\lambda^{(3)}$ modulating on LO.

Fig. 12 Mode transformation gate matrix, where the blue block denotes all modes pass, the orange block A_{\uparrow} mode ($|0\rangle$) passes, and the green block A_{\rightarrow} mode passes ($|1\rangle$).

Fig. 13 The computer simulation scheme of algorithm factorizing $15 = 3 \times 5$.

Fig. 14 The correlation measurement result of the superposition state of factorizing algorithm: (a) for mode A_{\uparrow} , and (b) for mode A_{\rightarrow} , where $E1 \sim E8$ represents $E_1 \sim E_8$ classical fields, and $\lambda 0 \sim \lambda 7$ the pseudorandom sequences modulated on LO $\lambda^{(0)} \sim \lambda^{(7)}$.